Navy Experimental Diving Unit
321 Bullfinch Rd.
Panama City, FL 32407-7015

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# ACCELERATED DECOMPRESSION USING OXYGEN FOR SUBMARINE RESCUE – SUMMARY REPORT AND OPERATIONAL GUIDANCE

NAVAL SEA SYSTEMS COMMAND
Navy Experimental Diving Unit

Authors: GARY LATSON
LCDR, MC, USNR
Principal Investigator

EDWARD FLYNN, M.D.
WAYNE GERTH, PhD.
EDWARD THALMANN, M.D.
JULIE MAURER, LCDR, MC, USNR
MICHAEL LOWE, LT, MSC, USNR

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19. ABSTRACT: In certain situations, a disabled submarine could become internally pressurized due to flooding, leakage of compressed gas supplies, or use of auxiliary breathing systems. This could result in the survivors being saturated with nitrogen at elevated pressures. Efficient submarine rescue requires that pressurized crewmembers be decompressed more rapidly than current procedures on air allow. NEDU has investigated the ability of oxygen to accelerate decompression following saturation with nitrogen-oxygen. Initial attempts resulted in an unexpectedly high incidence of severe decompression sickness. Subsequent decompression schedules including a period of isobaric oxygen breathing (pre-breathing) with a shorter total ascent time were significantly better than staged decompression of comparable length. Pre-breathing oxygen, or nitrogen-oxygen mixtures, is an effective decompression strategy. This report summarizes the experiments and presents decompression procedures for emergency use in submarine rescue.

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## ACCELERATED DECOMPRESSION USING OXYGEN FOR SUBMARINE RESCUE SUMMARY REPORT AND OPERATIONAL GUIDANCE

### EXECUTIVE SUMMARY

The U.S. Navy has a long-term commitment to maintain the ability to rescue survivors from a disabled submarine (DISSUB). The situation is complicated by the possibility that the internal pressure of the DISSUB may be raised due to flooding, leakage of gases from pressurized banks, or use of Emergency Air Breathing Systems. The survivors could be exposed to this increased pressure for a prolonged period of time, causing them to absorb inert gas in the same way that a diver does, and creating the need for a substantial period of decompression to avoid life threatening decompression sickness (DCS).

Currently, the principal U.S. Navy (USN) asset for the rescue of survivors from a DISSUB is the Deep Submergence Rescue Vehicle (DSRV), a mini-submarine designed to transfer rescuees from the DISSUB to a Mother Submarine (MOSUB) at internal DISSUB pressures up to 5 atmospheres absolute (ATA). Unfortunately, the current class of USN MOSUBs cannot be pressurized internally beyond 1 ATA. Rescuees arriving in the DSRV saturated with nitrogen at the pressure of the DISSUB, therefore, must be decompressed to atmospheric pressure in the DSRV prior to transfer to the MOSUB. The time needed for safe decompression on air begins to exceed the desired battery-recharge turnaround time for the DSRV at pressures as low as 2 ATA[1]. A more rapid means of decompression of rescuees is needed to avoid significant delays in the rescue cycle.

Breathing oxygen during decompression accelerates the elimination of inert gas from the body by minimizing the presence of nitrogen in the lungs, and thus maximizing the concentration gradient for inert gas from the blood to the lungs. This effectively reduces the time required to safely return to surface pressure. A field change has been approved for the DSRV that will allow rescuees to breathe 100% oxygen during decompression[1]. Theoretically, once the field change has been accomplished, decompression could be safely completed in the DSRV while the batteries are being recharged and minimal slowing of the rescue effort would occur. These studies also apply to the planned Submarine Rescue Diving and Recompression System (SRDRS); shortened decompression will eliminate recompression chamber availability as the rate-limiting step in the safe delivery of casualties to the surface.

The Navy Experimental Diving Unit (NEDU) has conducted a series of experiments to develop procedures for decompression of submarine rescuees using oxygen. USN decompression and oxygen toxicity risk models suggested that decompression on 100% oxygen could be conducted from saturation at pressures up to 60 feet of seawater (fsw) in as little as 4-6 hours with acceptable levels of decompression sickness and oxygen toxicity. Phase I of this study was a "proof of concept" trial, intended to test these predictions. Successful decompression from an equivalent air

depth (EAD*) of 40 fsw was followed by disconcerting results from the first trial at 50 fsw EAD; five out of eight subjects suffered decompression sickness following a six hour oxygen decompression. These unexpected results highlighted the need for further research into the use of oxygen to reduce decompression time.

In Phase II we demonstrated that breathing oxygen at the saturation depth prior to depressurization (referred to hereafter as "oxygen pre-breathing") increases the efficiency of oxygen decompression and we successfully developed a procedure allowing safe decompression from 50 fsw EAD in 7.5 hours.

In Phase III, we successfully applied the concept of oxygen pre-breathing to develop and test accelerated decompression schedules from 60 fsw EAD in 11.3 hours, less than one-third the time required for decompression on air.

The Operational Guidance at the end of this report provides recommended procedures for using oxygen decompression for submarine rescuees. This represents a major advance in readiness for submarine rescue missions.

* The term equivalent air depth (EAD) is used with nitrogen-oxygen exposures and refers to the depth on air at which the partial pressure of nitrogen would be equal to the partial pressure of nitrogen in the mixture at the exposure depth.

## CONTENTS

# INTRODUCTION

The U.S. Navy has a long-term commitment to maintain the ability to rescue survivors from a disabled submarine (DISSUB). The situation is complicated by the possibility that the internal pressure of the DISSUB may be raised due to flooding, leakage of gases from pressurized banks, or use of Emergency Air Breathing System. The survivors could be exposed to this increased pressure for a prolonged period of time, causing them to absorb inert gas in the same way that a diver does, and creating the need for a substantial period of decompression to avoid life threatening decompression sickness (DCS).

Currently, the principal U.S. Navy (USN) asset for the rescue of survivors from a DISSUB is the Deep Submergence Rescue Vehicle (DSRV). This mini-submarine is designed to transfer rescuees from the DISSUB to the awaiting safety of a Mother Submarine (MOSUB). Transfer from the DISSUB to the DSRV can take place at internal DISSUB pressures up to 5 atmospheres absolute (ATA). Unfortunately, the current class of USN MOSUBs cannot be pressurized internally beyond 1 ATA. Rescuees arriving in the DSRV saturated with nitrogen at the pressure of the DISSUB, therefore, must be decompressed to atmospheric pressure in the DSRV prior to transfer to the MOSUB. A major problem exists with current hardware and procedures. First, the current piping system in the DSRV is not well suited for conducting a controlled decompression. Second, the time needed for safe decompression on the normoxic nitrogen-oxygen (nitrox) atmosphere of the DSRV begins to exceed the desired battery-recharge turnaround time for the DSRV at pressures as low as 2 ATA. At not much higher pressures, decompression times exceed the 12-hour life support capacity of the DSRV.

A field change has been approved for the DSRV that will allow rescuees to breathe 100% oxygen during decompression[1]. Theoretically, once the field change has been accomplished, decompression could be safely completed in the DSRV while the batteries are being recharged and minimal slowing of the rescue effort would occur. These studies are also applicable to other current and future submarine rescue systems, such as the U.S. Navy Submarine Rescue Diving and Recompression System (SRDRS); the time required for decompression of rescuees is a major factor in determining the number and type of recompression chamber spaces needed to accomplish a successful rescue. Improved decompression procedures could greatly enhance the overall efficiency and safety of the operation.

The primary objective of this project was to develop decompression procedures to evacuate submarine rescuees in the most time-efficient manner possible with a low risk of *severe* DCS. To achieve this goal, a better understanding of the effects of oxygen upon decompression was necessary.

Breathing oxygen during decompression accelerates the elimination of inert gas from the body by minimizing the presence of nitrogen in the lungs, and thus maximizing the concentration gradient from the blood to the lungs, but these benefits are countered by

other physiologic and toxic effects of oxygen at elevated pressures. Two hypotheses may be invoked to explain the large discrepancy between the original predictions of the USN decompression models and the results observed in the trials during Phase I of this project. One hypothesis is that hyperbaric oxygen had no specific effects beyond those already accounted for in the models and that the models simply underestimated the amount of decompression time required for nitrogen removal from tissue. A second hypothesis is that the models adequately estimated the time required for nitrogen removal, but that hyperbaric oxygen had additional deleterious effects whose existence or magnitude was not adequately accounted for in the models. These effects could include slowing of nitrogen washout due to tissue vasoconstriction, inspired oxygen acting as an inert gas and contributing to bubble formation, or reduced decompression tolerance resulting from systemic oxygen toxicity[2, 3, 4, 5, 6]. Phase II attempted to distinguish between these two alternative hypotheses. In Phase III we applied the lessons learned from Phase II studies to accomplish safe decompression from an equivalent air depth of 60 fsw.

Current USN oxygen toxicity models as well as practical experience indicated that the planned exposures should be tolerable from the standpoint of oxygen toxicity. Nevertheless, we intended to verify these predictions with experimental data obtained from detailed pulmonary function studies before and after each exposure.

To gain more insight into the relationship between DCS and gas bubbles in the blood stream, called Venous Gas Emboli (VGE), we used Transthoracic 2-Dimensional Echocardiography (2-D echo) (a type of ultrasound imaging similar to that used for visualizing a fetus in pregnant women) to enhance our ability to detect VGE following decompression. This provided additional information regarding the degree of supersaturation of inert gases following the exposure.

This is a summary report; full details will be given in additional Navy Experimental Diving Unit (NEDU) reports.

## METHODS

### GENERAL

All experiments were reviewed and approved by the Committee for the Protection of Human Subjects, and conducted in the dry chambers of the Ocean Simulation Facility (OSF) located at NEDU. The chamber pressure, temperature, humidity, and gas composition were recorded electronically throughout the exposure and logged on a computerized data acquisition system.

Oxygen exposure was of concern during these experiments, both from the standpoint of central nervous system and pulmonary oxygen toxicity and from the standpoint of possible adverse effects that oxygen may have on the decompression. To focus these experiments on the viability of the accelerated decompression procedure itself, rather

than on the combined stress that pre-exposure to oxygen and accelerated decompression might produce, these studies did not use air, which would have contained a higher partial pressure of oxygen, during the saturation exposure. The diver-subjects were exposed to an oxygen level during saturation ($PO_2$ = 0.3 ATA) that is only slightly greater than normal. The only significant oxygen exposure, therefore, occurred during the experimental decompression. For this reason, pressures are given as both absolute pressure (depth) in feet of seawater (fsw), and as the Equivalent Air Depth (EAD).

Up to eight diver-subjects were tested on each saturation dive, which consisted of at least 72 hours of exposure to a nitrogen–oxygen mixture at gauge depths of 34, 42 or 50 fsw (40, 50, or 60 fsw EAD). The depth was controlled to ± 0.1 fsw whenever possible. While under saturation, the oxygen partial pressure was controlled at 0.30 ± 0.02 ATA. The 72-hour saturation time began when the diver-subjects left the surface and the diver-subjects were free to do whatever activity was deemed safe and unlikely to produce symptoms that could later be confused with decompression sickness or oxygen toxicity. (There were three exceptions to the planned 72 hour saturation time: dive # 13 was aborted after 54 hours due to electrical problems; dive # 7 was extended for 24 hours due to the passage of a hurricane; dive # 21 was extended for 24 hours due to a mishap with the oxygen delivery system requiring a delay and re-start of the decompression).

Following the saturation phase, the diver-subjects underwent an accelerated decompression to sea level pressure using the experimental schedules described below while breathing warm, humidified 95-100% oxygen. An exposure pattern of 30 minutes on oxygen and five minutes on air at the 50 fsw depth, and 60 minutes on oxygen and 15 minutes on air at the shallower depths, was used during pre-breathing and decompression to further reduce the likelihood of oxygen toxicity[7]. After each period of oxygen breathing, the diver-subjects removed the oxygen mask for a five or 15 minute air break. The break times are indicated in the schedules.

Oxygen delivery during decompression was via a semi-closed circuit rebreather, designated MK 18 MOD 1 EBA, developed by U.S. Navy Coastal Systems Station, Panama City, FL., for emergency use inside diving bells. These were modified for use with 100% oxygen and fitted with a locally-fabricated sampling port on the inhalation elbow to allow measurement of inspired gas composition using a mass spectrometer. Inspired oxygen levels were continuously monitored, and any time a diver-subject's inspired oxygen fell below 95%, the subject was instructed to "purge" the system for 10-20 seconds in order to raise the oxygen level. It should be noted that face-mask fit and seal were critical to maintaining these high inspired oxygen concentrations.

Every effort was made to ensure the comfort of the diver-subjects during the decompression. They were in a recumbent or semi-recumbent position, and were allowed to eat light snacks and drink fluids during air breaks. Chamber temperature was maintained at levels deemed comfortable to the subjects.

## EXPERIMENTAL SCHEDULES

The experimental decompression schedules are detailed in Appendix A. In this report, the term "total decompression time" (TDT) will refer to the total time of the experimental schedule, which includes the time that the subjects breathe oxygen at the saturation depth (pre-breathing), and the time of actual depressurization, which will be referred to as "total ascent time" (TAT), and the time for air breaks. The term "total oxygen time" will refer to the time spent breathing oxygen, either during pre-breathing or ascent, exclusive of air break time.

Phase I was a proof-of-concept trial using decompression schedules based on a simple, one-compartment Haldanian model in which nitrogen supersaturation was prohibited until the final ascent to the surface. Schedules I-1 (32 fsw/40 fsw EAD) and I-2 (42 fsw/50 fsw EAD) were computed assuming a 480 minute compartment washout half-time. Schedule I-1 proved successful at 40 fsw EAD, but in the first trial at 50 fsw EAD, Schedule I-2 produced a high incidence of DCS (5/8 subjects). Schedule I-2A lengthened the 50 fsw EAD decompression time by increasing the compartment half-time used in the calculations from 480 to 640 min.

Phase II was a comparison of schedules for decompression from a saturation depth of 50 fsw EAD with and without periods of oxygen pre-breathing prior to ascent. Schedule A1 has 8 hours of total oxygen time with no pre-breathing of oxygen at the saturation depth. Schedule A2 is identical to Schedule A1 with the exception that 4 hours of oxygen breathing are removed from the shallow 15 fsw stop and replaced with 4 hours of oxygen pre-breathing at the saturation depth. The intermediate stops and total oxygen time are identical. In effect, we compared schedules with nearly identical TDT, one of which had a period of pre-breathing and a reduced TAT.

Due to the success of schedule A2 (see results section), two additional schedules were proposed and tested. In Schedule A3, the oxygen pre-breathing time (and thus the TDT) was reduced by one hour. Schedule A4 reduced the pre-breathing time (and TDT) by an additional hour.

Phase III, with a saturation depth of 60 fsw AED, initially tested a schedule with 10 hours of oxygen time, which began with four 30-minute periods of oxygen pre-breathing at the saturation depth (Schedule III-A). The length of the pre-breathing period was chosen as a compromise between the theoretical advantage of isobaric nitrogen elimination and the risk of oxygen toxicity at this depth.

Due to the success of Schedule III-A, two additional schedules were tested. Both have approximately one hour less total oxygen time. Schedule III-AA has a shortened pre-breathing period. Schedule "AB" has the time reduction taken from the shallow decompression stops.

## MONITORING AND TREATMENT OF DCS

The diver-subjects remained under observation overnight at NEDU following decompression to facilitate post-dive testing, and they were monitored clinically for signs and symptoms of oxygen toxicity and decompression sickness. They also underwent neuropsychological testing before and after the dives, using both traditional paper based and verbal tests as well as a computerized test battery. (These results will be reported in a separate NEDU Technical Report[8]).

Treatment of DCS followed procedures in the U.S. Navy Diving Manual[9].

For the purposes of this experiment, four *classes* of decompression sickness were defined (not to be confused with the more commonly described *Types* of DCS, which we did not feel were descriptive enough for our purposes):

(1) Class I: Mild pain or aching in the joint(s), not exceeding an intensity of 3 out of 10 and not associated with limitation of motion. Minor numbness or paresthesia without objective neurological findings. Moderate fatigue. Skin itching or erythema.

(2) Class II: Pain or aching in the joint(s) greater than 3/10 or resulting in limitation of motion. Minor numbness or paresthesia with objective sensory findings. Minor motor weakness. Profound fatigue. Skin marbling. Class I symptoms that present while the diver is still under pressure.

(3) Class III: Major numbness or paresthesia with objective sensory findings. Major motor weakness. Gait or balance disturbance. Vertigo. Hearing abnormalities. Visual disturbance. Disturbance of consciousness. Cognitive or psychomotor change. Mild to moderate substernal distress, cough and/or shortness of breath.

(4) Class IV: Paralysis. Collapse. Loss of consciousness. Severe substernal distress, cough, and/or shortness of breath.

These descriptions were chosen to improve discrimination between cases of DCS based on severity. The accept/reject criteria for continuation of testing a schedule were based upon both number and severity of DCS cases[10,11,12]. Because these procedures are intended only for emergency use, a higher incidence of mild (Class I or II above) cases was deemed acceptable.

## MONITORING OF VENOUS GAS EMBOLI

At the completion of decompression, diver-subjects underwent transthoracic 2-D echocardiographic imaging at intervals of one to two hours for up to eighteen hours post decompression using a Hewlett Packard Sonus® 1000 diagnostic ultrasound cardiovascular imaging system with a 2.5 MHZ probe. VGE were quantified by the observer by a combination of visual and auditory criteria and a score was recorded at rest and after each extremity movement using the following scale, adapted (with modifications) from Webb et.al.[13, 14], Eftedal and Brubakk[15], and Kisman and Masurel[16].

**Table 1: Scale of 2-D Echo Bubble Scores**

| VGE Score | Description |
|---|---|
| 0 | Visual Image – No bubbles seen<br>Auditory Signal – No bubbles heard |
| 1 | Visual Image – Rare (<1 per sec) transient bubbles seen<br>Auditory Signal – Occasional signal heard (<1 per cardiac cycle) |
| 2 | Visual Image – Several discrete bubbles visible<br>Auditory Signal – Frequent discrete bubble signals |
| 3 | Visual Image – Multiple bubbles present, but not obscuring image<br>Auditory Signal – Bubbles in most cardiac cycles, but not obscuring heart sounds |
| 4 | Visual Image – Bubbles dominating image, may blur or obliterate chamber outlines ("white-out")<br>Auditory Signal – Strong bubble signals in each cardiac cycle, may obscure heart sounds |

## MONITORING OF PULMONARY FUNCTION

Because of the potential risk of pulmonary oxygen toxicity on these dives, all diver-subjects had pre-dive pulmonary function tests (PFTs) conducted to establish a baseline and then had the same series repeated periodically post-dive. The following parameters were measured:

1. Forced vital capacity (FVC) and expiratory flow rates
2. Slow vital capacity (SVC)
3. Diffusing capacity for carbon monoxide ($DL_{CO}$) and alveolar volume ($V_A$)

## RESULTS

### DECOMPRESSION SICKNESS

The most important outcome of these experiments was the incidence and severity of decompression sickness following use of each decompression schedule. The results of all dives in the series, including Phases I, II, and III are presented in Tables 2 and 3 below.

All cases of DCS during these experiments occurred after surfacing, and were treated initially according to U.S. Navy Treatment Table 6[9]. (A single exception was a subject who experienced a seizure during an oxygen breathing period; due to post-seizure confusion and combativeness, the initial treatment was aborted, the subject was returned to the surface, and was later treated according to U.S. Navy Treatment Table 9). Some subjects required additional treatments. Treatments are summarized in Table 3.

Phase I

The trials at an EAD of 40 fsw resulted in only one case of DCS in 23 subjects, which was a delayed case of subtle cognitive and visual changes, considered Class III (as described above).

Our first trial at an EAD of 50 fsw resulted in 5 cases of DCS out of 8 subjects. One case was Class III, and three cases were Class II. One of these subjects had paralysis of both lower extremities, another had bilateral moderately severe knee pain, and a third had weakness and sensory deficit of an upper extremity. Two other subjects had unilateral knee pain. This schedule was not repeated, and further trials using a schedule with approximately two hours of additional decompression time resulted in 3 cases of DCS in 20 subjects (one Class III and two Class II).

Phase II

Schedule A1, which had no pre-breathing of oxygen prior to ascending to the first decompression stop, resulted in 4 cases of DCS in 31 subjects (one Class II and three Class I). In contrast, Schedule A2, which began with four hours of oxygen pre-breathing prior to ascent to the first stop, resulted in no cases of DCS in 32 subjects. This difference was statistically significant at $p=0.053$ by Fisher's exact test. This schedule was then shortened by eliminating one hour of oxygen pre-breathing (Schedule A3), and this also resulted in no cases of DCS in 16 subjects. A comparison of results of Schedule A1 with the combined results of Schedules A2 and A3 is significant at a lower p value of $p=0.021$ by Fisher's exact test. The schedule was then shortened again by eliminating one additional hour of oxygen pre-breathing (Schedule A4), and this resulted in two cases of DCS in 15 subjects (both Class II).

## Phase III

The initial schedule (Phase III Schedule A) tested from 60 fsw EAD, with a total of ten hours of oxygen breathing, included two hours of oxygen pre-breathing at the saturation depth, and resulted in no cases of DCS in 15 subjects. A shorter schedule (Phase III, schedule AA), with one less hour of pre-breathing, and thus one less hour of total oxygen time, resulted in two cases of DCS in six subjects (both Class II). In order to help determine whether this poorer outcome was due to the reduction in pre-breathing time or the reduction in total decompression and oxygen time, we elected to test another schedule (Phase III, Schedule AB) which restored the pre-breathing time to two hours, but reduced the total decompression time by cutting an hour off the shallow portion of the decompression. This resulted in no cases of DCS in 8 subjects.

Table 2 shows the delay in onset and symptoms of each case. Appearance of DCS symptoms was delayed for several hours post surfacing in the majority of cases. The more severe cases tended to appear earlier.

**Table 2: Summary of DCS Results**

| DIVE # | DEPTH ACTUAL (fsw) | EAD DEPTH (fsw) | DECO SCHEDULE | TOTAL TIME (hr:min) | PRE-BREATHE (hr:min) | TOTAL $O_2$ (hr:min) | # SUBJ | # DCS (class) |
|---|---|---|---|---|---|---|---|---|
| 1,2,6 | 34 | 40 | Phase I Schedule 1 | 4:10 | None | 3:55 | 23 | 1 (III) |
| 3 | 42 | 50 | Phase I Schedule I-2 | 5:53 | None | 5:28 | 8 | 5 (III, II, II, II, II) |
| 4,5,7 | 42 | 50 | Phase I Schedule I-2A | 7:52 | None | 7:17 | 20 | 3 (III, II, II) |
| 8,10, 12,14 | 42 | 50 | Phase II Schedule A1 | 10:17 | None | 8:00 | 31 | 4 (II, I, I, I) |
| 9,11, 15,16 | 42 | 50 | Phase II Schedule A2 | 10:02 | 4:00 | 8:00 | 32 | 0 |
| 17,18 | 42 | 50 | Phase II Schedule A3 | 8:47 | 3:00 | 7:00 | 16 | 0 |
| 19,20 | 42 | 50 | Phase II Schedule A4 | 7:32 | 2:00 | 6:00 | 16 | 2 (II, II) |
| 21,22 | 50 | 60 | Phase III Schedule A | 12:30 | 2:00 | 10:00 | 15 | 0 |
| 23 | 50 | 60 | Phase III Schedule AA | 11:20 | 1:00 | 9:00 | 6 | 2 (II,II) |
| 24 | 50 | 60 | Phase III Schedule AB | 11:20 | 2:00 | 9:00 | 8 | 0 |

**Table 3: DCS Symptoms, Latency of Onset, and Treatment**

| Schedule | Symptoms | DCS Class | Onset Delay (hr) | Treatment |
|---|---|---|---|---|
| Phase I, 1 | Blurred vision/unclear thinking | III | 66 | TT6 (1 ext 60) |
| Phase I, 2 | Numbness/weakness Left arm | II | 16 | TT6 (3 ext 60, 1 ext 30) |
| Phase I, 2 | Bilateral knee pain | II | 4 | TT6 (1 ext 60) |
| Phase I, 2 | Bilat leg weakness/knee pain | III | 2 | TT6 (1 ext 60) |
| Phase I, 2 | Right knee pain | II | 4 | TT6 |
| Phase I, 2 | Right knee pain | II | 6 | TT6 |
| Phase I, 2A | Right knee pain | II | 2 | TT6 |
| Phase I, 2A | Left knee pain | II | 18 | TT6 |
| Phase I, 2A | Right leg numb/weak, pain Right foot | III | 4 | TT6 x 2 |
| Phase II, A1 | Right knee/ankle pain, numb toes | I | 24 | TT6 x2 |
| Phase II, A1 | Right hip/knee pain | I | 48 | TT6 |
| Phase II,A1 | Bilateral knee pain | I | 25 | Ext TT6x2, Kindwall |
| Phase II, A1 | L knee/R ankle pain, later headache, unclear thinking | II | 6 | Aborted TT6, $O_2$ seizure during Rx, TT9 x 2 |
| Phase II, A4 | Left knee pain | II | 5.5 | TT6 |
| Phase II, A4 | Left knee and ankle pain | II | 5 | TT6 |
| Phase III, AA | Left ankle pain | II | 9 | TT6 |
| Phase III, AA | Leg pain | II | 5.5 | TT6 |

## VENOUS GAS EMBOLI (ECHOCARDIOGRAPHY)

Data were analyzed for correlation of VGE scores and symptoms of DCS (if DCS occurred). Average VGE scores for each profile were compared with corresponding averages for the other profiles and a Bayesian analysis was completed to assess the DCS diagnostic power of VGE observations. The detailed data will be reported separately and maintained at NEDU for comparison to data from future studies. Selected results are presented below.

**Table 4: Venous Gas Emboli vs. Decompression Sickness**

| VGE GRADE | # SUBJECTS | # CASES DCS | % DCS |
|---|---|---|---|
| 0 | 118 | 4 | 3.4 |
| 1 | 21 | 2 | 9.5 |
| 2 | 19* | 6 | 31.6 |
| 3 | 16# | 1 | 6.3 |
| 4 | 8 | 4 | 50.0 |

*2 of these subjects were treated for DCS prior to the expected peak VGE – they may have reached higher VGE scores – if these are eliminated, 17 subjects with Grade 2 had 4 cases of DCS – 23.5%

# if the two subjects mentioned above are assumed to have reached VGE grade 3, then 18 subjects with grade 3 had 3 cases of DCS – 16.7%

## OXYGEN TOXICITY

Pulmonary oxygen toxicity was manifested by symptoms of irritation, cough, inspiratory discomfort, and mild dyspnea, but these symptoms resolved quickly in most cases. Pulmonary function testing revealed only small changes in vital capacity and diffusion capacity for carbon monoxide. In some subjects, changes in diffusion capacity for carbon monoxide persisted for several weeks.

There was one incident of a suspected mild CNS oxygen toxicity symptom - twitching of the lips in one subject during the second one-hour oxygen period during an aborted exposure to 42 fsw (50 fsw EAD). Another subject who developed Type I DCS after surfacing suffered a CNS toxicity seizure during treatment. Several subjects noted mild fingertip paresthesias in the later stages of the decompressions from 60 fsw EAD, which were felt to be a manifestation of prolonged oxygen exposure.

## DISCUSSION

Although the use of oxygen in decompression from shorter exposures is well established, heretofore there was very little data on its usefulness in decompression from saturation exposures. There was considerable debate about whether it would be useful due to the possibility of hyperbaric oxygen side effects, including slowing of the circulation due to vasoconstriction, the contribution of dissolved oxygen to bubble formation, or oxygen toxicity.

This experimental series demonstrated several important concepts. The results support the hypothesis that decompression from saturation exposures equivalent to air depths between 40 and 60 fsw can be accomplished in significantly less time than decompression with air, but the time required for safe decompression is greater than originally estimated. These results do not support the hypothesis that deleterious effects of oxygen are responsible for the initial poor outcomes seen in the Phase I

studies, because, in Phases II and III, decompression schedules which used oxygen at the deeper part of the schedule consistently produced better outcomes than schedules which used oxygen at shallower depths. Therefore, the additional time required for safe decompression is most likely due to slower than originally estimated tissue washout times.

Oxygen pre-breathing at the saturation depth prior to depressurization confers a significant advantage. The use of oxygen pre-breathing is effective at reducing both the total time of decompression and the total ascent time.

Tables 5A and 5B show the DCS incidence for each combination of oxygen pre-breathing time and total oxygen time tested. For each saturation depth, the number of subjects studied and the number of cases of decompression sickness observed for each combination is presented. Total oxygen time is the sum of the oxygen pre-breathing time and the oxygen decompression time, i.e., the total time on oxygen available for nitrogen washout. The numerator indicates the number of cases of DCS observed and the denominator indicates the number of individuals studied.

At the 50 fsw air equivalent depth, 7 decompression schedules were tested with widely varying pre-breathing times and total oxygen times. As stated above, a schedule with no pre-breathing and 8 hours of total oxygen (A1) produced 4 cases of DCS in 31 man-dives. A schedule with the same total oxygen time, 8 hours, including 4 hours of pre-breathing (A2), produced no cases of DCS in 32 exposures. The difference between these two schedules was statistically significant at $p = 0.053$ by Fisher's exact test. A shortened schedule (A3) with 7 hours of oxygen and 3 hours of pre-breathing also produced no cases of DCS in 16 exposures. When these results are combined, the difference between schedules including pre-breathing (A2 and A3) versus the schedule without pre-breathing (A1) is significant at a lower p value of $p = 0.21$ by Fisher's exact test, indicating an unequivocal benefit of pre-breathing.

A schedule with 8 hours of oxygen and 2 hours of pre-breathing also resulted in no cases of DCS, although only 8 subjects were tested on this combination (the results of this dive, # 13, are not included in statistical comparisons because the saturation time was only 54 hours). An attempt to shorten the total oxygen time to 6 hours with 2 hours of pre-breathing resulted in 2 cases of DCS in 15 subjects, but not nearly as severe as the schedule with 5.5 hours of total oxygen time and no pre-breathing (5 cases of DCS in 8 subjects).

At the 60 fsw air equivalent depth, three decompression schedules were tested. A schedule with 2 hours of oxygen pre-breathing and 10 hours of total oxygen produced no cases of DCS in 15 man-dives. A shortened schedule with only 1 hour pre-breathe and 9 hours of total oxygen produced 2 cases of DCS in 6 man-dives. However, a schedule with 9 hours of total oxygen and 2 hours of pre-breathing was free of DCS in 8 subjects. Due to the small sample size, a comparison of these schedules does not yield statistically significant results. These results suggest that a 9 hour schedule from

60 fsw is likely to produce a satisfactory result, but that two hours of pre-breathing may be necessary for this result to be achieved.

**Table 5A: Relationship between DCS incidence, oxygen pre-breathing time, and total oxygen time decompression time.**

**50 fsw Equivalent Air Depth** (42 fsw actual depth) (#cases DCS/#subjects)

| Pre-Breathing Time (hrs) | Total Oxygen Time (hrs) | | | | |
|---|---|---|---|---|---|
| | 5.5 | 6.0 | 7.0 | 7.3 | 8.0 |
| 0 | 5/8 | | | 3/20 | 4/31 |
| 1 | | | | | |
| 2 | | 2/15 | | | 0/8 |
| 3 | | | 0/16 | | |
| 4 | | | | | 0/32 |

**Table 5B: Relationship between DCS incidence, oxygen pre-breathing time, and total oxygen time decompression time.**

**60 fsw Equivalent Air Depth** (50 fsw actual depth) (#casesDCS/#subjects)

| Pre-Breathing Time (hrs) | Total Oxygen Time (hrs) | |
|---|---|---|
| | 9.0 | 10.0 |
| 0 | | |
| 1 | 2/6 | |
| 2 | 0/8 | 0/15 |

This beneficial effect of oxygen pre-breathing is due to elimination of some of the inert gas prior to any change in pressure ("isobaric de-nitrogenation"), which would logically reduce bubble formation from the remaining inert gas. This strategy is borrowed from studies in prevention of altitude-induced DCS, where a period of oxygen pre-breathing prior to ascent to altitude has been shown to be highly effective[13, 14]. Theoretically, decompression could be accomplished by pre-breathing oxygen at the saturation depth for a period sufficient to eliminate all inert gas, followed by depressurization to the surface. At shallow depths (less than 30 fsw EAD) this has been shown to be possible[17], but at deeper depths this approach would be limited by the problems of oxygen toxicity. Nevertheless, the statistically significant improvement in outcome between schedules that include pre-breathing and those that do not is strong evidence to support the use of a period of oxygen pre-breathing prior to ascent whenever possible.

While our sample sizes are too small to draw firm conclusions about the optimal duration of the pre-breathing time, these results imply that approximately two hours of

pre-breathing is needed to gain benefit; schedules with no pre-breathing, or only one hour of pre-breathing, were not as effective as schedules of similar total oxygen time with two or more hours of pre-breathing.

The latency of DCS onset following the use of these procedures may offer an opportunity for transport, triage, or interventions that could further reduce the incidence or severity of DCS, such as intravenous fluids and additional oxygen at surface. It must be emphasized, however, that this delay in onset of DCS occurred only after controlled decompression on oxygen, and it should not be confused with what could occur with shorter decompressions, or with decompression on air.

The occurrence of DCS affecting the Central Nervous System was an unexpected result. Prior experience with saturation decompression and physiologic assumptions about inert gas elimination from tissues led us to believe that bubble formation, and thus DCS, would not occur in the richly perfused tissues of the brain and spinal cord; we felt that the schedules allowed sufficient time for inert gas elimination in well perfused tissues. These unexpected results may lead to a revision of our assumptions about the dynamics of inert gas elimination from some tissues.

We anticipated a moderate incidence of DCS involving bone and joint tissues due to our assumption that these relatively short decompressions might not provide sufficient time for inert gas elimination from poorly perfused tissues, and the results were consistent with these predictions.

Pulmonary oxygen toxicity was mild and well tolerated by most subjects. In an emergency situation, toward which this research was directed, this level of pulmonary injury would not be mission limiting. However, there is definite evidence that pulmonary oxygen toxicity did occur, and this should be carefully considered if use of similar procedures is contemplated in non-emergency situations. Our use of air breaks probably mitigated the pulmonary effects considerably. In some emergency situations, the available equipment and time constraints could reduce the opportunity for air breaks; we caution that this would very likely result in a significant increase in pulmonary damage. Also, in a true submarine rescue situation, the rescuees may have a significant degree of pulmonary oxygen toxicity, or lung injury from smoke inhalation, prior to the start of oxygen decompression, which would likely result in more severe oxygen toxicity problems during the decompression. It is also possible that pre-existing pulmonary injury could impede inert gas elimination during decompression, or allow transpulmonic passage of gas bubbles, resulting in increased incidence and severity of DCS.

Central Nervous System (CNS) oxygen toxicity was not problematic, but we acknowledge that the risk of CNS toxicity, and therefore seizures is significant, particularly at partial pressures of oxygen exceeding 2.5 ATA (100% oxygen at ~50 fsw). We feel that the use of 30 minute oxygen periods at depths of 50 fsw and deeper helped to mitigate this risk, but we caution that the risk is not trivial, and should be considered, particularly if these procedures are contemplated for non-emergency use.

Personnel should be aware of this risk, and emergency procedures should be developed.

The data on VGE support a relationship between progressively higher VGE scores and increasing incidence of DCS. Bayesian analysis of this data shows that it could be a useful decision making tool. A VGE score of Grade 4 could be viewed as supportive evidence of DCS in cases with unclear symptomatology, or a significant warning sign and cause for increased vigilence, or possibly pre-emptive treatment, in patients without overt symptoms. While the VGE score alone is not diagnostic of DCS, it is a useful piece of clinical information that may be of value in triage or in unclear cases.

## SUBMARINE RESCUE OXYGEN DECOMPRESSION TABLE

The experimental data described in the previous sections, and other experience from earlier studies and decompression models, was used to guide the development of a final decompression table for use in submarine rescue (Table 6 below). It was originally intended for use with the DSRV, but is also suitable for use with the SRDRS or with any other rescue system capable of providing 100% oxygen and a controlled rate of decompression. Detailed procedures for use of the table are contained in Appendix A.

**Table 6. Submarine Rescue Oxygen Decompression Table**

| EAD (fsw) | $O_2$ Time at Depth ($O_2$ Pre-breathe)(min) | Decompression Stop Depth (fsw) | | | | | | Total $O_2$ Time (min) |
|---|---|---|---|---|---|---|---|---|
| | | 45 | 40 | 35 | 30 | 25 | 20 | |
| 20 | 0 | | | | | | | 0 |
| 25 | 70 | Oxygen Breathing Times at Depth (min) | | | | | | 70 |
| 30 | 140 | | | | | | | 140 |
| 35 | 120 | | | | | 40 | 40 | 200 |
| 40 | 120 | | | | 10 | 85 | 40 | 255 |
| 45 | 120 | | | 20 | 105 | 115 | 50 | 410 |
| 50 | 120 | | | 85 | 105 | 115 | 50 | 475 |
| 55 | 120 | | 55 | 95 | 105 | 115 | 50 | 540 |
| 60 | 120 | 30 | 85 | 95 | 105 | 115 | 50 | 600 |

Note 1: Oxygen breathing times are given in minutes.
Note 2. If air breaks are used, the time for each decompression stop may increase (see below)
Note 3: The time required to purge the closed-circuit breathing loop of nitrogen is included in the decompression stop time and does not need to be accounted for separately.

The goal was to produce decompression schedules that are reasonably safe, without being overly long. It must be emphasized that this table is intended for use in an emergency situation only, and that these schedules do not eliminate the risk of DCS completely; rather, they are our best advice for the most efficient way to decompress people when the impact of extended decompression times in the overall mission

scenario imposes even greater risks. There are multiple variables with regard to the condition of the subjects, the oxygen delivery system available, and the environmental conditions in which the decompression takes place (i.e., temperature, cramped spaces), which could have unpredictable effects upon the incidence of DCS using these procedures.

Individual decompression schedules within the Table were calculated using a one-compartment, single gas, deterministic decompression model. With this simple model, decompression schedules can be quickly recalculated in the field if unique operational circumstances arise.

The following assumptions were made in the calculation:

1. Only one compartment controls the decompression. This compartment exchanges nitrogen exponentially and has a variable half time depending on the equivalent air depth of the exposure. The half time is 480 minutes for equivalent depths of 40 fsw and shallower and 640 minutes for deeper equivalent depths.

2. Ascent to the first stop may take place when the nitrogen partial pressure in the compartment is 9 fsw less than the ambient pressure at that stop. The nitrogen washout needed to reach this value is achieved by pre-breathing of oxygen.

3. The depth of the first stop is selected to be the even 5-foot depth that is just shallower than the depth to which the DISSUB internal pressure would fall during a breathe-down of the atmosphere by the crew to an oxygen partial pressure of 0.2 ATA.

4. Ascent to subsequent stops may take place when the nitrogen partial pressure in the compartment is 9 fsw less than the ambient pressure at that stop.

5. Final ascent to the surface may take place when the compartmental nitrogen partial pressure reaches a level equivalent to 9 fsw greater than the ambient hydrostatic pressure on the surface. This would be equivalent to ascending directly to the surface from an air saturation dive at 20 fsw, which has been shown to result in a very low incidence of DCS.

6. To allow for mask leakage, the diver is assumed to inhale 90% oxygen rather than 100% oxygen.

The rationale for these assumptions is outlined briefly below.

In Phase II, we demonstrated that oxygen pre-breathing offered a statistically significant decompression advantage over decompression schedules of comparative length that did not include oxygen pre-breathing. The advantage of pre-breathing may relate to a number of factors, including: (1) washout of nitrogen prior to decompression which makes it harder for bubbles to form during decompression; (2) crushing of gas micronucleii which makes fewer "seeds" available for bubble formation; and (3)

inhibition of white blood cell adhesion preventing these cells from accumulating in areas of tissue injury and increasing tissue damage.

In Phase III, a combination of a 2-hour oxygen pre-breathe and a 7-hour oxygen decompression (9 hours total) appeared to produce a satisfactory decompression following a 60 fsw EAD exposure whereas a 1-hour pre-breathe and an 8-hour decompression (9 hours total) schedule did not. This result indicated that more than a 1-hour pre-breathe period was required to achieve safety. The 60 fsw, 2-hour pre-breathe, 7-hour decompression (9 hours total) schedule was chosen as a "safe" decompression for analysis and development of the ascent criteria given above.

A 2-hour pre-breathe at 60 fsw reduces the nitrogen tension in a 640 minute compartment to 9 fsw less than the ambient pressure at the 45 fsw first stop on the 9-hour schedule. This level of relative undersaturation for nitrogen is maintained throughout the decompression on the 9-hour schedule until ascent from the last stop is begun. Upon arrival at the surface, the nitrogen supersaturation becomes 9 fsw positive. The concept of a relative undersaturation for nitrogen during decompression followed by a final "drop out" to the surface was first applied in the development of decompression schedules by Hills[18]. Bubble formation is prevented during the decompression proper by a relative undersaturation of nitrogen and is only allowed to occur after the final ascent to the surface.

We used the 60 fsw results as the basis for calculation because of the long experience in saturation diving that what will work for deep exposures will also work for shallower exposures. Using these assumptions the model produced schedules that were extremely compatible with the experimental results observed at 50 and 60 fsw. At depths of 40 fsw and shallower, however, the schedules appeared longer than the experimental results dictated. Since total decompression time is of paramount importance in submarine rescue, these shallower schedules were calculated by keeping the supersaturation criteria the same but decreasing the compartment half-time from 640 minutes to 480 minutes. With this modification, the model produced 30 and 40 fsw schedules that were compatible with the experimental data obtained in Phase I and with the experience of the French Navy[17].

## CONCLUSIONS

1. The use of high inspired oxygen for acceleration of decompression from nitrox saturation is effective in reducing the total decompression time from saturation exposures up to an Equivalent Air Depth of 60 fsw.

2. The inclusion of a period of at least two hours of oxygen pre-breathing at the saturation depth prior to actual depressurization further reduces both the total decompression time and the total ascent time. Partial elimination of nitrogen prior to depressurization ("isobaric de-nitrogenation"), or resorption of gas micronuclei, is theorized to be primarily responsible for this beneficial effect.

3. Theoretical concerns regarding side effects of oxygen at hyperbaric pressures impeding decompression were not supported by the results of these experiments. Schedules which included the use of oxygen preferentially at higher pressures consistently resulted in better DCS outcomes.

4. The latency in onset of DCS after use of these procedures may provide an opportunity for transport or other interventions to reduce morbidity.

5. DCS involving the brain and spinal cord is a risk with accelerated decompression from saturation exposures, and this risk should be considered when faced with decisions to shorten decompression times in emergent situations.

6. 2-D echocardiography is a sensitive and reliable means of detecting VGE, and there is a relationship between high VGE scores and DCS. This relationship becomes significant when VGE levels reach Grade 4, and has some value with regard to the prediction or diagnosis of DCS. It may be a useful tool in the management of uncertain cases, or in the allocation of resources in a mass casualty situation.

7. Pulmonary oxygen toxicity was not of such severity as to preclude the use of these procedures in an emergency situation, but did cause significant discomfort in some subjects and did result in measurable, but reversible, changes in pulmonary function.

8. We recommend the Operational Guidance for Oxygen Decompression, contained in Appendix A, for immediate use in submarine rescue operations.

## DISCLAIMER

These studies were performed on healthy subjects, with no trauma, dehydration, thermal stress, malnutrition, or exposure to toxic atmospheric conditions. The condition of rescuees in a true disabled submarine situation could be much worse, and the safety of these procedures cannot be assured in those conditions. Furthermore, the inspired oxygen levels in these experiments were carefully optimized, and this would likely be very difficult in an actual rescue.

The procedure which follows in Appendix A is our best estimate of the minimum safe decompression, based on experience gained in these experiments. We do not regard these recommendations as definitive, and caution that the status of the subjects and the quality of the oxygen delivery system must be taken into consideration. If operationally feasible, we recommend extending the time for decompression on oxygen beyond these minimal times.

We do not advocate use of these procedures for non-emergent situations.

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# APPENDIX A

## GUIDANCE FOR OXYGEN DECOMPRESSION

### BACKGROUND

These decompression procedures are designed to be used in the Deep Submergence Rescue Vehicle (DSRV) fitted with Field Change 665, the Onboard Decompression System; however, they may be adapted for use in any rescue system, such as the planned Submarine Diving and Recompression System (SRDRS), with the capacity to provide safe delivery of oxygen for breathing during a controlled decompression. System-specific procedures should be developed according to the following guidelines. In systems without on-board decompression in the rescue vehicle, or transfer under pressure capability, it will probably be necessary to bring rescuees to surface pressure in order to transfer from the rescue vehicle to the recompression chamber. Limit the surface interval to 15 minutes or less whenever possible. Recompress the rescuees back to the DISSUB internal pressure, then begin the procedure described below.

The procedures are the result of test dives performed at the Navy Experimental Diving Unit (NEDU). The procedures provide for oxygen decompression from pressures up to 60 feet of seawater (fsw). Decompression from higher pressures is not addressed.

### BASIC PROCEDURE

Table A1 gives the decompression times on oxygen needed to safely return pressurized rescuees to normal atmospheric pressure. These times do not include air breaks (discussed below) which may increase the total time required by as much as 25%.

**Table A1. Submarine Rescue Oxygen Decompression Table**

| EAD (fsw) | $O_2$ Time at Depth ($O_2$ Pre-breathe)(min) | Decompression Stop Depth (fsw) | | | | | | Total $O_2$ Time (min) |
|---|---|---|---|---|---|---|---|---|
| | | 45 | 40 | 35 | 30 | 25 | 20 | |
| 20 | 0 | | | | | | | 0 |
| 25 | 70 | Oxygen Breathing Times at Depth (min) | | | | | | 70 |
| 30 | 140 | | | | | | | 140 |
| 35 | 120 | | | | | 40 | 40 | 200 |
| 40 | 120 | | | | 10 | 85 | 40 | 255 |
| 45 | 120 | | | 20 | 105 | 115 | 50 | 410 |
| 50 | 120 | | | 85 | 105 | 115 | 50 | 475 |
| 55 | 120 | | 55 | 95 | 105 | 115 | 50 | 540 |
| 60 | 120 | 30 | 85 | 95 | 105 | 115 | 50 | 600 |

Note 1: oxygen breathing times are given in minutes.
Note 2. If air breaks are used, the time for each decompression stop may increase (see below)
Note 3: The time required to purge the closed-circuit breathing loop of nitrogen is included in the decompression stop time and does not need to be accounted for separately.

To use Table A1, follow these five steps:

1. First calculate the rescuee's Equivalent Air Depth (EAD). This is necessary because the pressurized atmosphere of the DISSUB will likely have different partial pressures of oxygen and nitrogen than standard air. Decompression requirements are determined by the partial pressure of nitrogen in the tissues, and the use of the EAD is a convenient method of expressing the amount of nitrogen in the pressurized atmosphere. The EAD may be calculated from the following formula:

$$EAD = \frac{(D_{sub} + 33)(1 - FO_2)}{0.79} - 33$$

where: EAD = Equivalent Air Depth (fsw)
$D_{sub}$ = DISSUB internal pressure or depth (fsw)
$FO_2$ = Fractional concentration of oxygen in DISSUB atmosphere

If the information is available, use the highest $D_{sub}$ and the lowest $FO_2$ recorded in the last 24 hours when making the EAD calculation.

2. Enter Table A1 at the depth which is exactly equal or next greater than the calculated EAD. Begin the procedure by placing the rescuees on the oxygen breathing system. Breathe oxygen for the time indicated in the second column, "$O_2$ Time at Depth." Time is given in minutes. This oxygen period is termed "pre-breathing" because it takes place before decompression begins.

3. When the pre-breathing period is complete, decompress at 1-5 fsw/min to the first decompression stop indicated in the table.

4. Breathe oxygen at each decompression stop for the time indicated in the table. Oxygen breathing times are given in minutes.

5. Ascend between decompression stops at 1-5 fsw/min. Ascent time between stops is included in the subsequent stop time.

6. Upon completion of the last oxygen breathing period, remove the oxygen mask and decompress to atmospheric pressure at 1-5 fsw/min.

## MODIFICATIONS TO THE BASIC PROCEDURE

In emergency situations, it is highly likely that many factors could result in the need to vary or modify these procedures, and the on-scene Undersea Medical Officer should be allowed to do so if necessary to accommodate priorities. The following recommendations should be followed whenever possible.

Air Breaks during Pre-Breathing and Decompression

Periodic interruption of 100% oxygen breathing during pre-breathing and decompression is highly desirable to reduce the injurious effects of oxygen on the central nervous system and lung. Interruption of oxygen breathing may also be necessary to change $CO_2$ canisters in the closed-circuit breathing loop. Unexpected interruption of oxygen breathing may also occur because of rescuee illness or injury.

When at a pressure greater than 45 fsw (actual pressure, not EAD), interrupt oxygen breathing every 30 minutes with at least five minutes on air to minimize the risk of central nervous system oxygen toxicity (in this section, the term "air" refers to any approximately normoxic breathing mixture, or ambient cabin atmosphere).

When 45 fsw and shallower, interrupt oxygen breathing every two hours with at least 10 minutes on air. If the rescue timeline permits, interrupt oxygen breathing every 60 minutes with 15 minutes on air when 45 fsw and shallower. This pattern of 60 minutes on oxygen, 15 minutes on air is optimal for minimizing lung injury.

Once oxygen breathing is begun, consider any time spent on air to be "dead time," that is, not to count toward meeting the oxygen decompression requirement. Lengthen the time at each stop, and the total decompression time, correspondingly so that all the required time on oxygen during pre-breathing and at each stop is completed.

Optimally, rescuees should be on oxygen for at least 15 minutes prior to decompression to the first stop and should continue to breathe oxygen during decompression to the stop. This, however, is not a requirement. Ascent to the first decompression stop may be made on air or cabin atmosphere if necessary.

There is no contraindication to ascending between decompression stops while on air or cabin atmosphere. Ascent time, however, should not be included in the subsequent stop time since the rescuee is not on oxygen.

During oxygen pre-breathing, the time on air or cabin atmosphere should not exceed 15 minutes for each hour of oxygen breathed. Otherwise, some of the beneficial effects of oxygen pre-breathing will be lost. If the time on air exceeds 15 minutes per hour, add two minutes to the pre-breathing time for each minute spent on air beyond the 15 minute allowance.

Oxygen Pre-breathing in DISSUB or during transit

Oxygen pre-breathing in the Disabled Submarine (DISSUB), or in the rescue vehicle during transit, could be used to shorten the time required for decompression at the final destination. The decision to employ oxygen pre-breathing in the DISSUB or rescue vehicle during transit would depend on the availability of suitable equipment to supply oxygen, the risk of fire in the rescue vehicle cabin, the extent to which rescuees are already suffering from pulmonary oxygen toxicity or other pulmonary injury, and the

anticipated risk of central nervous system oxygen toxicity. 100 % oxygen should not be breathed at an actual pressure greater than 60 fsw due to the risk of CNS oxygen toxicity.

Reduce the oxygen time in Table A1 by one minute for each minute spent pre-breathing oxygen in the DISSUB or during transit. Subtract oxygen time from the pre-breathing time in Table 1 first, then from the decompression stops, beginning with the shallowest decompression stop first.

> Example: A rescuee on the 45 fsw EAD schedule breathes oxygen for 180 minutes during transit. The 120 minute pre-breathe requirement has already been satisfied, so direct ascent to the first stop is allowed. The remaining 60 minutes is subtracted first from the 20 fsw stop (50 minutes), then from the 25 fsw stop (10 minutes). The rescuee may surface after completing 105 minutes on oxygen at 25 fsw.

Use the effective pre-breathing time, not the actual pre-breathing time in the DISSUB or during transit, to determine how much decompression time to subtract from Table A1. The effective pre-breathing time is the actual pre-breathing time minus two minutes for each minute spent on DISSUB or DSRV atmosphere beyond the 15 minute allowance per hour of oxygen.

> Example: A rescuee prebreathes oxygen in the DISSUB for two 60 minute periods separated by a 15 minute air break, then breathes air for 60 minutes in the DSRV during transit from the DISSUB to the MOSUB. How much decompression time should be subtracted from Table 1?
>
> Solution: Thirty minutes on air is allowed for the two hours of oxygen breathed. The rescuee, however, has spent a total of 75 minutes on air (the 15 minute air break + the 60 minute transit in the DSRV). The excess air time is 45 minutes (75-30). The effective oxygen pre-breathing time therefore is 120 - (2 x 45) = 30 minutes. Subtract 30 minutes from the oxygen decompression time in Table A1.

For DISSUB pressures up to an EAD of 40 fsw, all of the oxygen decompression time required by Table A1 can generally be completed by pre-breathing without a significant risk of pulmonary or CNS oxygen toxicity.

For DISSUB pressures greater than an EAD of 40 fsw, the allowable pre-breathing time will be governed primarily by the extent to which pulmonary symptoms are already present and by the actual DISSUB pressure, which governs the inspired oxygen partial pressure during the pre-breathing period. The actual DISSUB pressure may be significantly less than the equivalent air depth due to oxygen consumption in the DISSUB. This lower actual pressure allows for a greater use of oxygen pre-breathing. As a general rule, limit oxygen pre-breathing to 240 minutes at an actual DISSUB pressure up to 40 fsw and to 120 minutes at an actual pressure of 41-60 fsw. 100 %

oxygen should not be breathed at an actual pressure greater than 60 fsw due to the risk of CNS oxygen toxicity.

Shortened Decompression

Operational circumstances may force shortening of the prescribed decompression. Shortening of the decompression can be expected to increase both the incidence and severity of decompression sickness, but the exact risks are difficult to predict because the data are extremely limited and current decompression risk models do not describe saturation decompression on oxygen very well. Moderate shortening can be expected to produce neurological and cardiovascular decompression sickness while extreme shortening such as direct ascent to the surface from pressures of 50-60 fsw EAD, may produce death in individuals left untreated. Shortened decompression may also put operators at a significant risk for decompression sickness. Decompression should not be shortened unless other operational factors outweigh this significant risk.

## DECOMPRESSION OF SYSTEM OPERATORS AND TENDERS

In many cases, system constraints will force system operators and inside medical tenders to decompress at the same time as the rescuees. To achieve safe decompression, operators and tenders must breathe oxygen during the decompression for the times indicated in Table A2. Oxygen breathing may be synchronized with rescuee breathing cycles and follow the same pattern of time on oxygen and time on air. Oxygen breathing by operators and tenders should be timed so that the last minute of oxygen breathing is completed when the rescuees are ready to make the final decompression to the surface.

In Table A2, Operator Exposure Time is defined as the elapsed time from initial pressurization of the rescue vehicle until the rescuees begin oxygen pre-breathing after mating to the MOSUB or SRDRS chamber. Enter the table at the Operator Exposure Time that is exactly equal to or next greater than the actual exposure time. Read down to the EAD schedule being used by the rescuees. Find the oxygen breathing time in minutes.

During the pre-breathing period, operators and tenders will be exposed to an additional period of time at the DISSUB depth beyond that already included in the Operator Exposure Time. This additional time has been incorportated into the calculation of the decompression requirement in Table 2 and need not be accounted for separately.

If the rescuees breathe oxygen during transit, some decompression schedules may be shortened to the point where the oxygen breathing requirement of the operators and tenders exceeds the remaining decompression time. This is especially true of shallow schedules with long operator exposure times. In these cases, the operators should begin oxygen breathing during transit along with the rescuees so that they have an opportunity to complete all the required oxygen time prior to decompression to the

surface. Use the operator's effective pre-breathing time (see calculation above) when computing his remaining oxygen decompression time.

**Table A2. System Operator/Tender Oxygen Breathing Times (minutes)**

| EAD (fsw) Schedule[1] | Operator Exposure Time (minutes)[2] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0[3] | 120 | 240 | 360 | 480 | 600 | 720 |
| 25 | 0 | 0 | 0 | 20 | 40 | 60 | 70 |
| 30 | 0 | 10 | 40 | 70 | 100 | 120 | 140 |
| 35 | 0 | 30 | 80 | 110 | 140 | 160 | 180 |
| 40 | 15 | 70 | 120 | 150 | 180 | 210 | 230 |
| 45 | 70 | 120 | 160 | 190 | 220 | 250 | 270 |
| 50 | 100 | 150 | 190 | 230 | 260 | 280 | 300 |
| 55 | 130 | 180 | 220 | 260 | 280 | 300 | 320 |
| 60 | 160 | 210 | 250 | 280 | 310 | 330 | 350 |

Note 1: Use the same decompression schedule as the rescuees, based on the EAD, and breathe oxygen for the times indicated.
Note 2: Operator Exposure Time is the elapsed time from initial pressurization of the rescue vehicle until the rescuees begin breathing oxygen after mating to the MOSUB or SRDRS chamber or decanting to a deck recompression chamber.
Note 3: Use the zero column for a tender who locks into the recompression chamber at the beginning of the oxygen pre-breathing period and remains in the chamber throughout the remaining decompression.

## TREATMENT OF DECOMPRESSION SICKNESS AND ARTERIAL GAS EMBOLISM IN SUBMARINE RESCUE OPERATIONS

Decompression sickness or arterial gas embolism (AGE) could occur in any DISSUB scenario, either after use of the schedules in the previous section, or in the likely event that conditions could not allow use of the procedures due to time or equipment constraints. Therefore, treatment of a DISSUB casualty must take into account not only the fact that the rescuee has decompression sickness or arterial gas embolism, but also that he may have omitted a significant amount of saturation decompression. Standard treatments may resolve the immediate clinical problem, but not satisfy the patient's saturation decompression obligation. Failure to take this omitted decompression time into account may result in inadequate treatment with subsequent recurrence of symptoms. The following procedures are designed to provide both recompression therapy and the total oxygen time needed to resolve the patient's remaining decompression obligation.

### PROCEDURE

1. Allocate patients for recompression treatment following the appropriate DISSUB triage algorithm.

2. Compress to 60 fsw and begin treatment with oxygen according to U.S. Navy Treatment Table 6. Recompression deeper than 60 fsw should not be undertaken unless it is certain that chamber resources can be devoted exclusively to that patient, for example, at a shore-based referral site.

3. Follow Treatment Table 6 to the completion of the 30 fsw stop using allowed extensions at 60 and 30 fsw to resolve symptoms, as needed.

4. Add the time spent on oxygen during the current treatment to any time spent on oxygen during saturation decompression or prior recompression treatments to calculate the patient's total oxygen time to that point.

5. Determine the oxygen time required for safe decompression from the DISSUB depth using Table A3 below. Subtract the patient's total oxygen time from the required oxygen time to determine the patient's remaining omitted oxygen decompression time.

**Table A3. Required Oxygen Time**

| DISSUB Equivalent Air Depth (fsw) | Required Oxygen Time (min) |
|---|---|
| 20 | 0 |
| 25 | 70 |
| 30 | 140 |
| 35 | 200 |
| 40 | 255 |
| 45 | 410 |
| 50 | 475 |
| 55 | 540 |
| 60 | 600 |

6. If no omitted oxygen decompression time remains, complete Table 6 by surfacing from 30 fsw on oxygen at 1 fsw/min. If less than 170 minutes of omitted oxygen decompression time remain, ascend to 15 fsw at 1 fsw/min on oxygen, complete the remaining oxygen time at 15 fsw, then ascend to the surface on oxygen at 1 fsw/min. If more than 170 minutes of omitted decompression time remain, complete any time in excess of 170 minutes at 30 fsw, then ascend to 15 fsw at 1 fsw/min on oxygen, complete 170 minutes on oxygen at 15 fsw, then ascend to the surface on oxygen at 1 fsw/min. Oxygen breathing during the additional time at 30 and 15 fsw should be interrupted every 60 minutes with a 15 minute air break continuing the pattern of oxygen exposure begun at 30 fsw on Table 6.

7. If necessary, surface asymptomatic or nearly asymptomatic patients before completion of treatment to make room in the chamber for more emergent cases. Reduce the patient's omitted oxygen decompression time by the amount of oxygen

time completed during the treatment. If omitted oxygen decompression time remains, additional oxygen recompression treatment should be administered when feasible under the triage scheme. In the interim, these patients should breathe surface oxygen and remain at rest in the supine position.

8. Once treatment is initiated, complete one Treatment Table 6 at a minimum even if the omitted oxygen decompression time is zero (i.e., the calculated amount of necessary oxygen decompression was given prior to onset of DCS). Interrupt treatment only if premature surfacing is required to accommodate a more emergent case.

9. Allocate patients with recurrence of symptoms or new symptoms post treatment to recompression according to the triage rules. Once all the omitted oxygen decompression time has been completed, these patients may be managed as described in the USN Diving Manual.

10. Asymptomatic rescuees with omitted oxygen decompression time are at significant risk for decompression sickness. These individuals should be recompressed and treated as above whenever circumstances permit. While awaiting recompression, these individuals should breathe surface oxygen and remain at rest in the supine position. Surface oxygen should be continued for a period not less than three times the omitted oxygen decompression time. All rescuees with omitted oxygen decompression time should eventually receive recompression therapy as soon as practical to prevent late occurrence of DCS.

11. The on-scene Undersea Medical Officer should have the discretion to vary these procedures due to other needs of the patient, allocation of resources, or other considerations.

## SUBMARINE ESCAPE AND RESCUE MEDICAL ADVISORY PANEL

The Medical Officers of Submarine Development Squadron Five, San Diego, CA, have primary responsibility for issues related to SUBSUNK emergencies, and should serve as the primary point of contact for inquiries (commercial phone (619) 553-7099, DSN 553-7099). A Submarine Escape and Rescue Medical Advisory Panel has also been established at the Navy Experimental Diving Unit to provide up-to-date decompression information in the event of a SUBSUNK emergency. The advisory panel is composed of knowledgeable specialists and researchers with special expertise in selected areas, and is available to respond to questions regarding the use of these procedures. The Panel Coordinator is the Medical Director of the Navy Experimental Diving Unit and can be reached at (850) 230-3100 or DSN 436-4351.

## REFERENCES


1. Naval Sea Systems, *U.S. Navy Diving Manual*, Vol. #5, Rev. 4., Naval Sea Systems Command, NAVSEA SS521-AG-PRO-010 (Arlington, VA: U.S. Navy, 1999), Chapter 21.

## APPENDIX B - DECOMPRESSION SCHEDULES

This Appendix provides details of the experimental schedules used during manned testing. These are not recommended for routine use.

**Table B1: Comparison of Experimental Schedules Phase I: Decompression without Pre-Breathing from 40 and 50 fsw EAD**

| Schedule | EAD | TDT (hr) | $O_2$ time (hr) | Pre-breathe time (hr) | DCS Risk** (%) | UPTD* (units) |
|---|---|---|---|---|---|---|
| I-1 | 40 | 4.17 | 3.92 | 0 | 5.5 | 443 |
| I-2 | 50 | 5.87 | 5.47 | 0 | 9.6 | 686 |
| I-2A | 50 | 7.85 | 7.28 | 0 | 4.8 | 913 |

**Table B2: Summary of Experimental Schedules Phase II: Decompression with/without Pre-Breathing from 50 fsw EAD**

| **Schedule** | **TDT (hr)** | **$O_2$ time (hr)** | **Pre-breathe time (hr)** | **DCS Risk** (%)** | **UPTD* (units)** |
|---|---|---|---|---|---|
| II-A1 | 10.28 | 8.00 | 0 | 4.2 | 866 |
| II-A2 | 10.03 | 8.00 | 4 | 4.2 | 1239 |
| II-A3 | 8.78 | 7.00 | 3 | 5.1 | 1047 |
| II-A4 | 7.53 | 6.00 | 2 | 6.0 | 855 |

**Table B3: Summary of Experimental Schedules Phase III: Decompression with Pre-Breathing from 60 fsw EAD**

| **Schedule** | **TDT (hr)** | **$O_2$ time (hr)** | **Pre-breathe time (hr)** | **DCS Risk** (%)** | **UPTD* (units)** |
|---|---|---|---|---|---|
| III-A | 12.50 | 10.00 | 2 | 4.3 | 1609 |
| III-AA | 11.33 | 9.00 | 1 | 5.2 | 1389 |
| III-AB | 11.33 | 9.00 | 2 | 5.5 | 1490 |

* UPTD – Unit Pulmonary Toxicity Dose, a measure of oxygen exposure based on partial pressure of oxygen and time, calculated with the method of Harabin et. al.[1] using a value of 95% for inspired oxygen

** Predicted risk of DCS, estimated by the Fd7Vk3SSM decompression model, Gerth[2, 3] et. al.

**Schedule I-1**

Tested from a saturation pressure of 40 fsw EAD (34 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 34-25 | $N_2$ / $O_2$ | 2 | 2 |
| 25 | Oxygen | 63 | 65 |
| 25-20 | Oxygen | 1 | 66 |
| 20 | Oxygen | 52 | 118 |
| 20 | Air | 10 | 128 |
| 20 | Oxygen | 19 | 147 |
| 20-15 | Oxygen | 1 | 148 |
| 15 | Oxygen | 99 | 247 |
| 15-0 | Air | 3 | 250 |

Total Decompression Time: 250 min = 4.17 hr
Total Oxygen Time: 235 min = 3.92 hr

**Schedule I-2**

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42-35 | $N_2$ / $O_2$ | 1 | 1 |
| 35 | Oxygen | 30 | 31 |
| 35-30 | Oxygen | 1 | 32 |
| 30 | Oxygen | 59 | 91 |
| 30-25 | Air | 1 | 92 |
| 25 | Air | 9 | 101 |
| 25 | Oxygen | 66 | 167 |
| 25-20 | Oxygen | 1 | 168 |
| 20 | Oxygen | 52 | 220 |
| 20 | Air | 10 | 230 |
| 20 | Oxygen | 19 | 249 |
| 20-15 | Oxygen | 1 | 250 |
| 15 | Oxygen | 99 | 349 |
| 15-0 | Air | 3 | 352 |

Total Decompression Time: 352 min = 5.87 hr
Total Oxygen Time: 328 min = 5.47 hr

## Schedule I-2A

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42-35 | $N_2$ / $O_2$ | 1 | 1 |
| 35 | Oxygen | 40 | 41 |
| 35-30 | Oxygen | 1 | 42 |
| 30 | Oxygen | 44 | 86 |
| 30 | Air | 10 | 96 |
| 30 | Oxygen | 35 | 131 |
| 30-25 | Oxygen | 1 | 132 |
| 25 | Oxygen | 87 | 219 |
| 25-20 | Air | 1 | 220 |
| 20 | Air | 9 | 229 |
| 20 | Oxygen | 96 | 325 |
| 20-15 | Oxygen | 1 | 326 |
| 15 | Oxygen | 19 | 345 |
| 15 | Air | 10 | 355 |
| 15 | Oxygen | 113 | 468 |
| 15-0 | Air | 3 | 471 |

Total Decompression Time: 471 min = 7.85 hr
Total Oxygen Time: 437 min = 7.28 hr

## Schedule II-A1

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42-25 | $N_2 / O_2$ | 17 | 17 |
| 25 | Oxygen | 60 | 77 |
| 25 | Air | 15 | 92 |
| 25 | Oxygen | 30 | 122 |
| 25-20 | Oxygen | 5 | 127 |
| 20 | Oxygen | 25 | 152 |
| 20 | Air | 15 | 167 |
| 20 | Oxygen | 60 | 227 |
| 20-15 | Air | 5 | 232 |
| 15 | Air | 10 | 242 |
| 15 | Oxygen | 60 | 302 |
| 15 | Air | 15 | 317 |
| 15 | Oxygen | 60 | 377 |
| 15 | Air | 15 | 392 |
| 15 | Oxygen | 60 | 452 |
| 15 | Air | 15 | 467 |
| 15 | Oxygen | 60 | 527 |
| 15 | Air | 15 | 542 |
| 15 | Oxygen | 60 | 602 |
| 15-0 | Air | 15 | 617 |

Total Decompression Time: 617 min = 10.28 hr
Total Oxygen Time: 480 min = 8.00 hr

**Schedule II-A2**

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42 | Oxygen | 60 | 60 |
| 42 | Air | 15 | 75 |
| 42 | Oxygen | 60 | 135 |
| 42 | Air | 15 | 150 |
| 42 | Oxygen | 60 | 210 |
| 42 | Air | 15 | 225 |
| 42 | Oxygen | 60 | 285 |
| 42-25 | Air | 17 | 302 |
| 25 | Oxygen | 60 | 362 |
| 25 | Air | 15 | 377 |
| 25 | Oxygen | 30 | 407 |
| 25-20 | Oxygen | 5 | 412 |
| 20 | Oxygen | 25 | 437 |
| 20 | Air | 15 | 452 |
| 20 | Oxygen | 60 | 512 |
| 20-15 | Air | 5 | 517 |
| 15 | Air | 10 | 527 |
| 15 | Oxygen | 60 | 587 |
| 15-0 | Air | 15 | 602 |

Total Decompression Time: 602 min = 10.03 hr
Total Oxygen Time: 480 min = 8.00 hours

**Schedule II-A3**

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42 | Oxygen | 60 | 60 |
| 42 | Air | 15 | 75 |
| 42 | Oxygen | 60 | 135 |
| 42 | Air | 15 | 150 |
| 42 | Oxygen | 60 | 210 |
| 42-25 | Air | 17 | 227 |
| 25 | Oxygen | 60 | 287 |
| 25 | Air | 15 | 302 |
| 25 | Oxygen | 30 | 332 |
| 25-20 | Oxygen | 5 | 337 |
| 20 | Oxygen | 25 | 362 |
| 20 | Air | 15 | 377 |
| 20 | Oxygen | 60 | 437 |
| 20-15 | Air | 5 | 442 |
| 15 | Air | 10 | 452 |
| 15 | Oxygen | 60 | 512 |
| 15-0 | Air | 15 | 527 |

Total Decompression Time: 527 min = 8.78 hr
Total Oxygen Time: 420 min = 7.00 hr

## Schedule II-A4

Tested from a saturation pressure of 50 fsw EAD (42 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 42 | Oxygen | 60 | 60 |
| 42 | Air | 15 | 75 |
| 42 | Oxygen | 60 | 135 |
| 42-25 | Air | 17 | 152 |
| 25 | Oxygen | 60 | 212 |
| 25 | Air | 15 | 227 |
| 25 | Oxygen | 30 | 257 |
| 25-20 | Oxygen | 5 | 262 |
| 20 | Oxygen | 25 | 287 |
| 20 | Air | 15 | 302 |
| 20 | Oxygen | 60 | 362 |
| 20-15 | Air | 5 | 367 |
| 15 | Air | 10 | 377 |
| 15 | Oxygen | 60 | 437 |
| 15-0 | Air | 15 | 452 |

Total Decompression Time: 452 min = 7.53 hr
Total Oxygen Time: 360 min = 6.00 hr

## Schedule III-A

Tested from a saturation pressure of 60 fsw EAD (50 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 50 | Oxygen | 30 | 30 |
| 50 | Air | 5 | 35 |
| 50 | Oxygen | 30 | 65 |
| 50 | Air | 5 | 70 |
| 50 | Oxygen | 30 | 100 |
| 50 | Air | 5 | 105 |
| 50 | Oxygen | 30 | 135 |
| 50-45 | Air | 5 | 140 |
| 45 | Air | 10 | 150 |
| 45 | Oxygen | 15 | 165 |
| 45-40 | Oxygen | 5 | 170 |
| 40 | Oxygen | 40 | 210 |
| 40 | Air | 15 | 225 |
| 40 | Oxygen | 25 | 250 |
| 40-35 | Oxygen | 5 | 255 |
| 35 | Oxygen | 30 | 285 |
| 35 | Air | 15 | 300 |
| 35 | Oxygen | 40 | 340 |
| 35-30 | Oxygen | 5 | 345 |
| 30 | Oxygen | 15 | 360 |
| 30 | Air | 15 | 375 |
| 30 | Oxygen | 60 | 435 |
| 30-25 | Air | 5 | 440 |
| 25 | Air | 10 | 450 |
| 25 | Oxygen | 60 | 510 |
| 25 | Air | 15 | 525 |
| 25 | Oxygen | 30 | 555 |
| 25-20 | Oxygen | 5 | 560 |
| 20 | Oxygen | 25 | 585 |
| 20 | Air | 15 | 600 |
| 20 | Oxygen | 60 | 660 |
| 20 | Air | 15 | 675 |
| 20 | Oxygen | 10 | 685 |
| 20-15 | Oxygen | 5 | 690 |
| 15 | Oxygen | 45 | 735 |
| 15-0 | Air | 15 | 750 |

Total decompression time: 750 min = 12.50 hr
Total oxygen time: 600 min = 10.00 hr

## Schedule III-AA

Tested from a saturation pressure of 60 fsw EAD (50 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 50 | Oxygen | 30 | 30 |
| 50 | Air | 5 | 35 |
| 50 | Oxygen | 30 | 65 |
| 50-45 | Air | 5 | 70 |
| 45 | Air | 10 | 80 |
| 45 | Oxygen | 15 | 95 |
| 45-40 | Oxygen | 5 | 100 |
| 40 | Oxygen | 40 | 140 |
| 40 | Air | 15 | 155 |
| 40 | Oxygen | 25 | 180 |
| 40-35 | Oxygen | 5 | 185 |
| 35 | Oxygen | 30 | 215 |
| 35 | Air | 15 | 230 |
| 35 | Oxygen | 40 | 270 |
| 35-30 | Oxygen | 5 | 275 |
| 30 | Oxygen | 15 | 290 |
| 30 | Air | 15 | 305 |
| 30 | Oxygen | 60 | 365 |
| 30-25 | Air | 5 | 370 |
| 25 | Air | 10 | 380 |
| 25 | Oxygen | 60 | 440 |
| 25 | Air | 15 | 455 |
| 25 | Oxygen | 30 | 485 |
| 25-20 | Oxygen | 5 | 490 |
| 20 | Oxygen | 25 | 515 |
| 20 | Air | 15 | 530 |
| 20 | Oxygen | 60 | 590 |
| 20 | Air | 15 | 605 |
| 20 | Oxygen | 10 | 615 |
| 20-15 | Oxygen | 5 | 620 |
| 15 | Oxygen | 45 | 665 |
| 15-0 | Air | 15 | 680 |

Total decompression time: 680 min = 11.33 hr
Total oxygen time: 540 min = 9.00 hr

## Schedule III-AB

Tested from a saturation pressure of 60 fsw EAD (50 fsw actual pressure)

| Actual Pressure (fsw) | Gas | Time (min) | Elapsed Time (min) |
|---|---|---|---|
| 50 | Oxygen | 30 | 30 |
| 50 | Air | 5 | 35 |
| 50 | Oxygen | 30 | 65 |
| 50 | Air | 5 | 70 |
| 50 | Oxygen | 30 | 100 |
| 50 | Air | 5 | 105 |
| 50 | Oxygen | 30 | 135 |
| 50-45 | Air | 5 | 140 |
| 45 | Air | 10 | 150 |
| 45 | Oxygen | 15 | 165 |
| 45-40 | Oxygen | 5 | 170 |
| 40 | Oxygen | 40 | 210 |
| 40 | Air | 15 | 225 |
| 40 | Oxygen | 25 | 250 |
| 40-35 | Oxygen | 5 | 255 |
| 35 | Oxygen | 30 | 285 |
| 35 | Air | 15 | 300 |
| 35 | Oxygen | 40 | 340 |
| 35-30 | Oxygen | 5 | 345 |
| 30 | Oxygen | 15 | 360 |
| 30 | Air | 15 | 375 |
| 30 | Oxygen | 60 | 435 |
| 30-25 | Air | 5 | 440 |
| 25 | Air | 10 | 450 |
| 25 | Oxygen | 60 | 510 |
| 25 | Air | 15 | 525 |
| 25 | Oxygen | 30 | 555 |
| 25-20 | Oxygen | 5 | 560 |
| 20 | Oxygen | 25 | 585 |
| 20 | Air | 15 | 600 |
| 20 | Oxygen | 60 | 660 |
| 20-0 | Air | 20 | 680 |

Total decompression time: 680 min = 11.33 hr
Total oxygen time: 540 min = 9.00 hr

## REFERENCES

1. Harabin, A. L., et al., "An Analysis of Decrements in Vital Capacity as an Index of Pulmonary Oxygen Toxicity," J. of Applied Physiology, 63 (3) (1987): 1130-1135.

2. Gerth, W. A., Vann, R. D., "Probabilistic Gas and Bubble Dynamics Models of Decompression Sickness Occurrence in Air and Nitrogen-Oxygen Diving," Undersea Hyper. Med., 24 (1997): 275-292.

3. Gerth, W. A., Decompression Model Fd7Vk3SSM, (Navy Experimental Diving Unit, 2000), unpublished.